Kinematic Analysis of the Collision Avoidance Behavior of Cliff Swallows

By

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Senior Honors Thesis

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May 4, 2021

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Abstract

One interesting aspect of animal behavior is that each individual organism responds to stimuli independently of other organisms, barring the extensive pheromone communication of social insects. The behavior of conspecifics provides a significant source of stimuli that merit reaction, considering that, by definition, they utilize the same resources. In the case of American Cliff Swallows (*Petrochelidon pyrrhonota*), one of these resources is mud, which is used for nesting material. Despite requiring the same resources, these birds live in large colonies and must constantly respond to each other's' behavior, particularly when they fly quickly, in large groups, to collect mud from the same site. Furthermore, social situations between conspecifics might merit distinct types of behavior depending on the type of group activity. We sought to determine how Cliff Swallows avoid crashing into each other during high velocity low altitude group flight. We used a MATLAB-based software package to track individual members of a swallow colony as they approached a mud patch, using 3 different video angles to determine their 3D position during flight. Using this position data, we calculated their relative position, velocity and acceleration. Notable variables we observed were the mean and minimum bird to bird distances of each significant bird, changes in their closing and departing speeds and angles, and the ratio of their closing speed to average flight speed. We found that the birds do actively engage in collision avoidance behavior. However, we also found that Cliff Swallows approach each other much more closely during this mud-gathering behavior than has been observed in flocks of other similar-size birds. We also found that nest gathering interactions are distinct from other Cliff Swallow behaviors, such as tandem flights. This research can provide a deeper

understanding of how individual animals respond to stimuli and avoid collisions, potentially inspiring crash avoidance algorithms in self-driving vehicles.

1 Introduction

Cliff Swallows (*Petrochelidon pyrrhonota*) are birds that traditionally build their nests on cliffs and other steep surfaces. The birds use mud to construct their nests (Brown & Brown, 1988). They live in large colonies (Emlen Jr, 1952) and all nest and brood at the same time, meaning that all of the birds are simultaneously constructing their nests in preparation for egg laying. Thus, the birds tend to congregate at mud sources as they commute to and from the nest site, bringing them into close proximity in the air and increasing the chances of an aerial collision.

Mid-air collision with another bird can be a significant hindrance to the birds, but is rarely observed, making it likely that the birds actively avoid collisions. However, the manner in which the birds decide how to adjust their course to consistently avoid collision is unknown. This question of collision avoidance is a topic of recent investigation because animals show substantially greater capability in avoiding collisions than man made self-directed vehicles do. Researchers seek to discover what behavior systems organisms use to analyze external stimuli and make decisions to prevent collisions, hoping to apply this knowledge to improve engineered systems' performance (Brace et al., 2016). For example, Brace and her colleagues Brace and her colleagues used two aerial models, bats (*Myotis velifer*) and birds (*Petrochelidon pyrrhonota*), along with an aquatic model, *Danio aequipinnatus*, for comparison with a collision avoidance algorithm, finding that the algorithm was consistent with the behavior of the organisms. Another study performed by Parikh et. al. (2019) observes similar behaviors in Chimney Swifts (*Chaetura pelagica*), another colonial bird species that flies and nests in large groups. These behaviors make them similar to Cliff Swallows. However, while Chimney Swifts are observed to enter their chimney colonies at relatively high velocities, the Cliff Swallows in this study fly much slower and much closer together than the Chimney Swifts (Parikh et al, 2019).

We hypothesized that Cliff Swallows change their flight trajectories to avoid collisions. Furthermore, we expected that collision avoidance begins at a similar time to anticipated collision as in the Chimney Swift results, but at a different (and smaller) distance between birds due to the slower flight speeds used by the Cliff Swallows. Following results from Parikh et. al. we predicted that collision avoidance begins when the birds are 0.15 seconds away from a predicted collision (2019). We addressed these hypotheses by using high-speed 3D videography to collect kinematic data from a flock of Cliff Swallows gathering nest building mud near a colony in Missoula, Montana. This data was analyzed using the DLTdv7 MATLAB (The MathWorks, Natick, MA, USA) package (Hedrick, 2008). An alternate explanation for the observed flight behavior is the absence of active collision avoidance due to low probability and cost of collision in such slow and low altitude conditions.

We found that members of this swallow colony were consistently able to avoid collisions and that they showed less evidence of course correction than might be expected from such close proximity flight. This suggests that the birds are able to predict each other's movements a substantial distance from their common target, eliminating the need for dramatic trajectory changes. However, we did conclude that active collision avoidance takes place.

2 Methods

The primary method of flight observation we used was multi-camera videography. This technique involves assembling synchronized videos of bird flight from several different angles as raw data (Figure 1). Then, we used a structure-from-motion algorithm followed by Direct Linear Transformation (DLT) implemented in MATLAB (Theriault et. al., 2014) to calibrate and resolve the different camera views to create 3D flight paths for each of the observed birds. This technique can be used to study the birds' "kinematics, collective motion, migration, ... ecology and cognition (Ling et. al., 2018)." Once the 3D flight paths were documented, we were able to analyze the flight kinematics of the birds, thereby determining the speed, position and direction of each of the birds through their observed flight trajectories. In addition to the video analysis, we created a simulation of close bird interactions with and without active collision avoidance to provide a point of reference to help understand the observed flight behavior.

2.1 Video Description

We used a previously collected set of Cliff Swallow videos taken by Dr. Brandon Jackson to analyze the behavior of these birds in flight (Figure 1). The birds themselves were recorded on June 3, 2012 while flying to and from a 2 m^2 mud patch at the Fort Missoula Field Research Station in Missoula, Montana. The videos were taken in grayscale to maximize image resolution and data storage efficiency. The grayscale nature of the videos did introduce some difficulty during the tracking process.

Cliff Swallows have both dark and light coloration patches in their plumage, with dark plumage taking more surface area than light plumage. Most of the time tracking the birds this was convenient because the light gray plumage would contrast with a dark background while the dark gray plumage would contrast with a light background (Figure 2), but tracking became problematic when the birds flew in front of darker trees. Overall, ease of determining a bird's position in a given frame varied with the background it was flying against. We tried to track the same part of the birds' anatomy through each flight path, preferring to mark the thorax in each frame (Figure 2). However, sometimes the wings or tail would be the only distinguishable feature of the bird. These minor inconsistencies were addressed by a low-pass filtering process described in kinematic analysis (Figure 3). The 3D reconstruction error was able to place the birds within the 10cm scale of their body size.

2.2 Video Analysis

Three cameras (IDT N5r, IDT Vision Technologies, Pasadena CA USA) were positioned around the mud patch in question and took 3 synchronized videos of the same place and time from the 3 angles of the cameras (Figure 1). We used the easyCamera camera placement model to determine the best way to position the three cameras (Theriault et. al., 2014). Our goals of camera placement were to provide the best possible interaction between reconstruction volume and the resolution at which the birds were observed (Theriault et. al., 2014). Our cameras were positioned in such a manner as to minimize reconstruction uncertainty (Figure 1). Using the DLTdv7 MATLAB package (Hedrick, 2008) we were able to mark the position of a given bird in at least two different camera angles to provide its 3D position in a given frame following camera calibration using the easyWand program (Theriault et. al., 2014). This program requires the cameras to be synchronized and is calibrated by placing physical objects a predetermined distance apart to give the cameras a physical reference for distance and 3D position (Theriault et. al., 2014). One camera angle, named Video 3, was more magnified than Videos 1 and 2, but was poorly focused. Because of its magnification, Video 3 would theoretically give a higher accuracy tag for 3D positioning. In practice, the poor focus made it difficult to distinguish the birds from the background. The reconstruction volume, the volume of space in which we could discern 3D position, was 4000m^3. Each video consisted of 475 frames, showing 4.75 seconds shot at 100 frames per second. Of the 429 flight paths we were able to track at all, 76 were matched in such a manner as to produce a 3D flight path. These 3D tracks combine to a total of 325 seconds of bird flight.

Close interactions between the birds were defined as being within 30 cm of each other for ≥ 10 frames. Individual birds could not be identified between videos, so each documented flight track was treated as a unique event, much like the treatment of Cliff Swallow tandem flights in Shelton et. al. (2014).

2.3 Kinematic Analysis

Once we acquired the bird positions via stereo videography, we used kinematic analysis to calculate results related to the motion of the birds. These results include the flight speed, velocity vector, acceleration vector, and relative distance to neighbor birds. As a first step, a low-pass filter was used to smooth the trajectories. This removes the effect of frame-to-frame variability in which part of the bird was digitized and other 3D reconstruction artifacts. We used a 5 Hz low-pass digital Butterworth filter implemented in MATLAB (Figure 3); this cutoff frequency is below the approximately 12.3 Hz flapping frequency of the birds (Shelton et. al., 2014), so the filter also removes the effect of flapping on the instantaneous velocity, acceleration and 3D position of the birds (Figure 3). Velocities and accelerations were then computed by fitting a spline function to the smoothed trajectory and analytically differentiating it, giving these two vectors. Flight speed was calculated as the magnitude of the velocity vector, and the radius of curvature of the flight path was calculated from the velocity and acceleration following Shelton et al. (2014). Relative distance to neighbor birds was calculated from the smoothed positions, and cases where two birds came within 30 cm of one another for 10 or more frames (0.1 seconds) were categorized as a close interaction.

During these close interaction events we computed additional kinematic parameters from the pair of trajectories: the closing speed (the average rate at which the birds draw closer to one another during a single interaction event between two birds), the departing speed (the average rate at which the birds get further apart once they pass the minimum distance of a given interaction), the angle between the flight trajectories of the two birds during approach and departure from the point of minimum distance, and the changes in speed and angle before and after that minimum distance point. All of these variables are defined for the interaction pair, not the birds individually.

2.4 Simulation of Collision Avoidance

We simulated collision avoidance and non-avoidance interactions between swallows to help understand the results obtained from the real birds. Because the observed bird motion was mostly in the horizontal plane, the simulation was conducted in 2D as follows. First two agents (i.e., simulated birds) were placed on a cartesian grid at a random radius of between 0 and 5 meters from the origin and at a random rotation of 0 to 360 degrees using draws from two uniform random distributions. Cases where the agents started with 0.3 m of one another were discarded. After placement, the agents were randomly assigned a speed from 1 to 6 meters per second from a uniform distribution and given an initial flight direction back toward the origin. In cases where no collision avoidance was specified, the agents proceeded to move in a straight line until the end of the simulation. In cases where collision avoidance was enabled, each agent turned away from the other at a rate of 250 degrees per second (while maintaining their randomly assigned constant speed) once the distance between agents was less than 0.3 meters. Agents that did not come with 0.3 meters of one another proceeded in straight paths with no avoidance. After the conclusion of each simulated interaction, the minimum agent-agent distance, the average closing speed, and average agent speed were recorded. The simulation was repeated 1,000 times to reveal the range of possible outcomes.

It is important to note that alternate simulation assumptions were attempted. Alterations to assumed rates of direction change and bird speed altered the exact characteristics of the simulated behavior, but did not change the broad pattern of a linear relationship between minimum agent-agent distance and the ratio of average closing speed to average agent speed, nor did these changes remove the empty lower left corner of the distance to speed ratio chart that we later found to characterize active collision avoidance. We must also note that the simulation was not meant to be a high-fidelity recreation of avoidance maneuvers and that neither 250 nor 100 degrees/second necessarily resembles swallow behavior.

3 Results

Analysis of the video recordings yielded 349 tracks (Figure 4). Our program was able to calculate a number of variables regarding the bird flights, including the overall average speed of the birds, their average closing and departing speeds regarding interactions, average change in speed over the course of interaction, average closing and departing angles over the course of interaction, interaction elevation and both mean and minimum bird-bird distances for each individual close interaction (Table 1). We were also able to determine the mean, maximum, minimum and median values of these variables across all documented interactions (Table 2). Of the 349 flight paths tracked at the mud patch over the course of data analysis, 76 showed close interactions worthy of investigation as defined by our criteria of a minimum distance of ≤ 30cm sustained for at least 10 frames.

3.1 Characterization of Individual Instances of Avoidance

After tracking the flight paths of the birds, we were able to determine the birds' speed, acceleration, and angles of approach and departure in relation to each other. We sought to determine which birds showed the strongest change in direction over the course of their interactions. The greater the change in speed or angle, the greater the signs of avoidance behavior in a given interaction. For example, Birds 19 and 39 showed strong signs of collision avoidance in both values (Figure 5), while birds 32 and 44 showed few signs in both values (Figure 6, Table 1). The average change in speed and angle of all close interactions were greater than zero, implying that the swallows expressed some degree of collision avoidance (Table 2). We cannot yet determine exactly when the birds first noticed each other's' presence and began executing their avoidance behaviors. We also did not identify any consistent rules of the road. For example, we did not find that the faster moving bird is the one that makes an avoidance maneuver. Instead, both birds appear to react to avoid a collision.

3.2 Group Analysis of All Close Interactions

We analyzed the behavior of all the interacting birds by plotting their ratios of average closing speed to average overall flight speed against their minimum distances. The speed ratio is a useful indicator of the direction at which the birds approach each other, as it represents the relationship between the interacting birds' individual speeds and the conditions of their approach. A ratio value near zero suggests near parallel flight, as parallel flight means that the birds do not grow closer to each other, regardless of how quickly either bird is moving of its own volition. A ratio value near one implies a 60-degree approach angle, and a ratio value near two reflects a head-on approach. In a head-on approach, the two birds are, by definition, drawing closer to each other twice as quickly as their average speed. The speed ratio is meant to be interpreted as a behavioral justification, rather than a mathematical or physical one.

The plot of the birds' speed ratios and minimum distances was then compared with two sets of computer simulations of birds interacting in a similar manner. One was programmed to show no avoidance behaviors, resulting in theoretical crashes and many close encounters, and another was programmed to show avoidance, resulting in no theoretical crashes and larger minimum encounter distances (Figure 7). The collected Cliff Swallow data set resembled the avoidance plot. None of the birds crashed into each other, and none of the birds reached a minimum distance of 5cm. Furthermore, the linear regression of the collected data set displayed statistical significance, with a p value of 1.0×10^{-4}, meaning the birds did not behave at random; we conclude that they actively avoided each other (Figure 7).

4 Discussion

Our recordings of the Cliff Swallows revealed several cases where the birds had a close interaction (Table 1). In most of these the differences in closing and departing angles are consistent with a course change by one or more birds involved in the interaction. In other cases where there was no apparent course correction. We found that the Cliff Swallows engage in avoidance behavior due to the lack of observed collisions in the data set and by the presence of changes in the birds' flight speed and direction between the approaching and departing segments of each close interaction.

4.1 Comparison with Cliff Swallow Tandem Flights

While the average flight speed during this nest gathering behavior was 4.5 m/s (3.3 m/s during close interactions), the average speed of Cliff Swallows during tandem flight is 7.0 m/s (Shelton et. al. 2014). Tandem flight behavior occurs when one bird chases another, commonly to prevent nest parasitism, when one bird lays eggs in another's nest (Brown & Brown, 1989). Tandem flight is a competitive interaction between two birds, likely requiring a higher speed as an intimidation tactic that is not necessary in nest gathering interactions. Furthermore, the Cliff Swallows may employ different behavioral models when engaging in tandem flight and nest gathering interactions, considering that the former is a conscious decision of both birds to interact, while the latter is a result of one bird pursuing the other.

Tandem flights do not easily fit into the minimum distance and closing speed to flight speed paradigm identified here as a signature of active collision avoidance, because during the tandem pursuit the birds remain approximately the same distance apart for many wingbeats as they match courses. Even over short timescales when the birds get momentarily closer to one another, the closing speed to flight speed ratio is likely to be quite low, indicating a more distant interaction according to the results here. Indeed, the goal of the chasing bird in a tandem flight interaction is to maintain nearly parallel motion with the target bird, resulting in low closing speed to flight speed ratios. In contrast, the nest material gathering interactions examined here reflect a wide variety of speed ratios, suggesting the interactions are more haphazard on the part of the birds.

4.2 Comparison with Chimney Swifts

The Cliff Swallow roosting colony and nearby mud-patch provides an aggregation point that led to birds landing and taking off in crowded airspace. This overall task is most comparable to a recent study of Chimney Swift landing kinematics and avoidance behavior (Parikh et. al., 2019). However, although both cases involve groups of birds landing in proximity to one another, there are some differences between the behaviors. Specifically, the Chimney Swifts approached a single chimney with a very small opening (0.64 m^2) at high velocity (Parikh et. al., 2019), while the Cliff Swallows congregate at a much larger mud patch (~2 m^2). Despite these differences, both species dropped to similar flight speeds during close encounters (3.5 m/s for the Chimney Swifts, 3.3 m/s for the Cliff Swallows) (Parikh et. al., 2019). With respect to bird-bird distances, the Chimney Swifts have a median minimum distance during chimney entry of 0.51 m (Parikh et. al., 2019). The Cliff Swallows in this study showed a median minimum distance of 0.20 m when interacting near the mud patch, which is substantially less than the Chimney Swifts. The Cliff Swallows were also closer to the ground, so the former species was likely less concerned with the risk of a midair collision than the latter. Additionally, while the Chimney Swifts could only enter the chimney two at a time at most (Parikh et. al., 2019), Cliff Swallows covered the surface of the mud patch, meaning there were simply more birds at the site of interest for the Cliff Swallows to be close to.

The variable that gave the strongest indication of collision avoidance behavior in this study of Cliff Swallows was the linear regression of minimum bird-bird distance and the ratio of closing speed to average speed. Parikh et. al., due to the much smaller number of birds present at any particular moment, used a comparison of minimum bird-bird distance and the angle of the two birds' velocity vectors in reference to the target chimney, defined as a neighbor angle, to characterize collision avoidance in Chimney Swifts (2019). This variable was able to characterize the competitive nature of chimney entry interaction, showing that, in a close encounter, a Chimney swift with a neighbor angle of about 90° was frequently successful in chimney entry; Swifts who failed to enter in a given interaction had an average neighbor angle of 60° (Parikh et. al., 2019). We were not able to characterize a similar set hierarchy in terms of precedence in Cliff Swallow collision avoidance behavior during nesting material gathering. This may be a result of decreased competitive urgency resulting from the larger size of the mud patch. The differences in target area between the chimney opening and the mud patch surface may create distinct enough behavior that our velocity ratio is useful with the Cliff Swallows where it may not be for the Chimney Swifts, and vice versa in regards to neighbor angle. Alternatively, the velocity ratio may be useful in defining instances of collision avoidance in crowded groups, while neighbor angle may be useful in characterizing competitive dominance during avoidance interactions with fewer participants.

4.3 Future Work

Although the Cliff Swallows demonstrated collision avoidance behavior, in several cases avoidance was by a surprisingly small amount, or with a surprisingly small course change. For example, three of the selected interactions showed a Δ Angle < 10° (Table 1). It is possible that the swallows can determine potential collisions from a greater distance away and make minor adjustments that we did not detect with an analysis focused on what the birds do once within 0.3 m of one another. This could be explored in the future by analyzing the directionality of the birds and the rate of change in distance between each other. If this is the case, we may be able to use these close interactions to mark which bird tracks warrant analysis for any sort of prior collision avoidance behavior between the birds.

Another aspect of flight behavior that was not characterized in this analysis was the flapping frequency of the Cliff Swallows. We analyzed the kinematics and the geometric flight paths of the birds without considering the wingbeat frequency of the birds. This contrasts with research into the feeding behavior of Barn Swallows where the flapping frequency was 6.6 + 3.2 Hz (Warrick et. al., 2016). This research also analyzes both the air speed and ground speed of the Barn Swallows in both straight and turning flight trajectories (Warrick et. al., 2016). Further research may demonstrate that wingbeat frequency changes during close interactions; we predict it should increase to give the animal more power for flight maneuvers. Feeding behavior is far more frequent than this material gathering behavior, which is an annual occurrence.

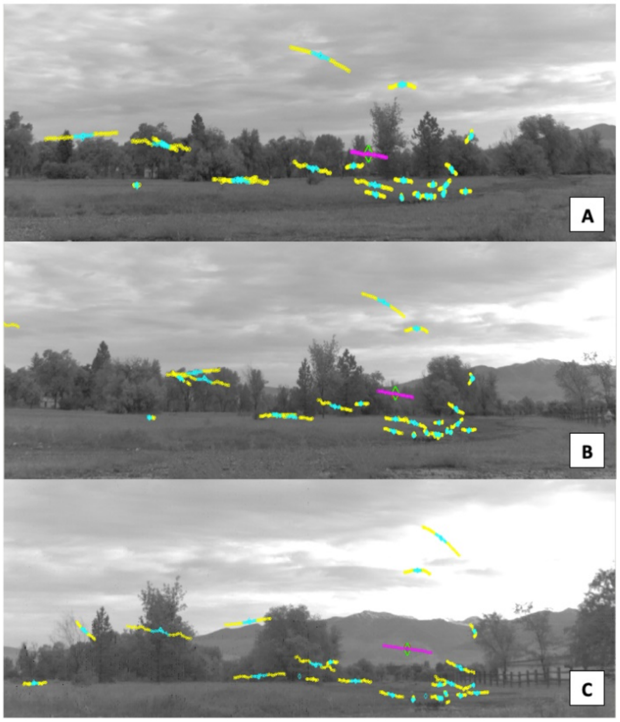
5 Conclusions

By analyzing the 3D position of Cliff Swallows during communal nest gathering behavior, we were able to conclude that these birds are consistently able to avoid crashing into each other during low altitude, close proximity flight. Furthermore, by showing that nest material gathering interactions are markedly distinct from tandem flight behavior, we can conclude that these organisms are able to recognize and react to different social and environmental situations and adjust behavioral models. By demonstrating this behavior, we can proceed to analyze their behavior more closely in search of defining their preferred behavioral model, which can serve as an inspiration for engineered collision avoidance systems.

6 Acknowledgements

I would like to recognize the Tyson Hedrick Lab at the University of North Carolina at Chapel Hill for conducting research into biological flight kinematics. Professor Hedrick himself was incredibly supportive through this process and consistently provides mentorship to undergraduate students seeking to begin their careers in biological research. I would also like to thank Dr. Brandon Jackson for collecting the video data that was used to produce these findings. I would like to thank the National Science Foundation (IOS-1253276 to TLH) and the Office of Naval Research (N0001410109452 to TLH and others) for providing the funding that enabled the collection of these videos and the development of the DLTdv7 program. Finally, I must thank the UNC-CH Biology Department for conducting the undergraduate honors thesis program and Professor Amy Maddox for providing guidance on compiling an original research thesis.

7 Figures



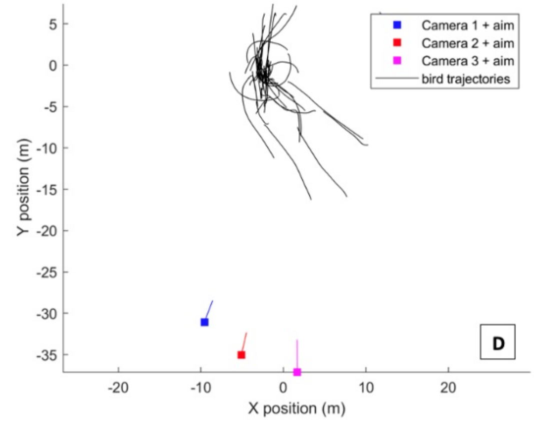


Figure 1. Stereoscopic Video Camera Views and Positions Relative to the mud patch. A) Camera 1 view with a selected bird. B) Camera 2 view with the same selected bird. C) Camera 3 view with the same selected bird. D) Overhead view of the three cameras and their associated view directions in relation to the mud patch and all flight trajectories. The mud patch is located at the graph's origin.

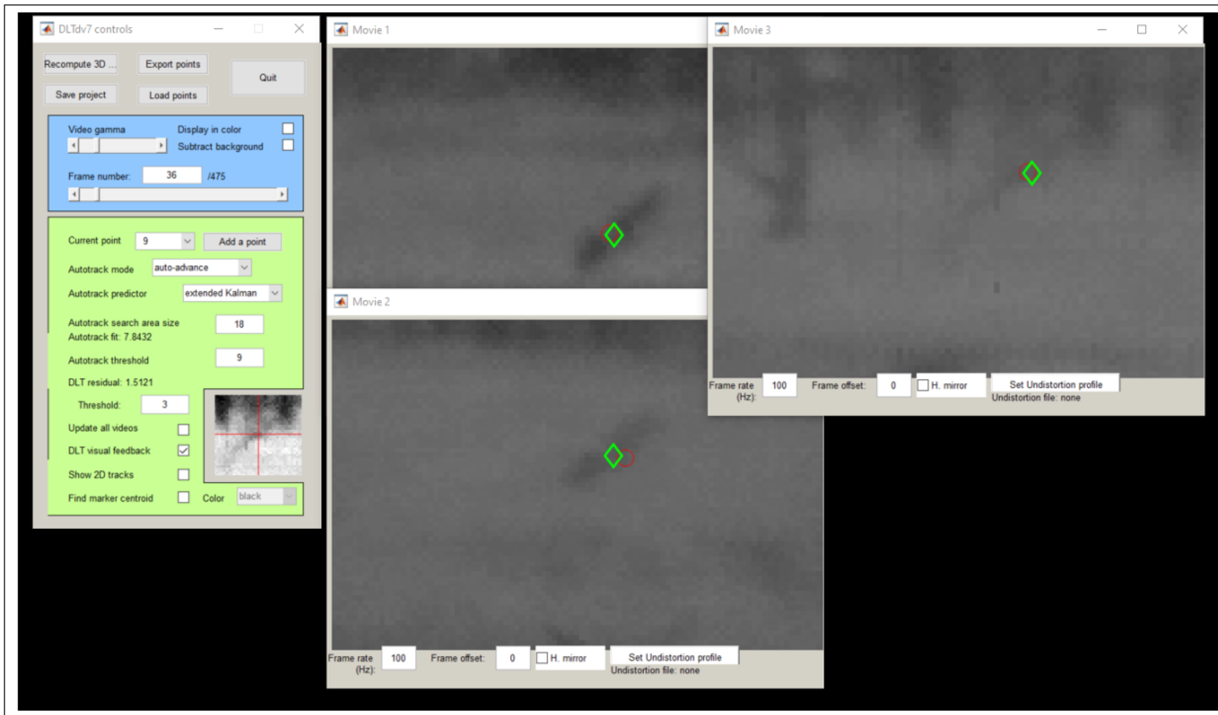


Figure 2. Visual Display of the DLTdv7 Program Controls and Video Analysis. DLTdv7 controls) displays the frame of the video sets being observed, the bird whose track is being constructed (Current point), and quality of life features that do not merit discussion. Movies 1, 2, & 3) Display three alternate views of bird 9 and the position notation the program uses to construct a 3D flight track. The red circles on each of the camera frames indicate where the bird was manually marked in the program, the green diamond indicates the bird's projected 3D position when compared with data from the other 2 frames.

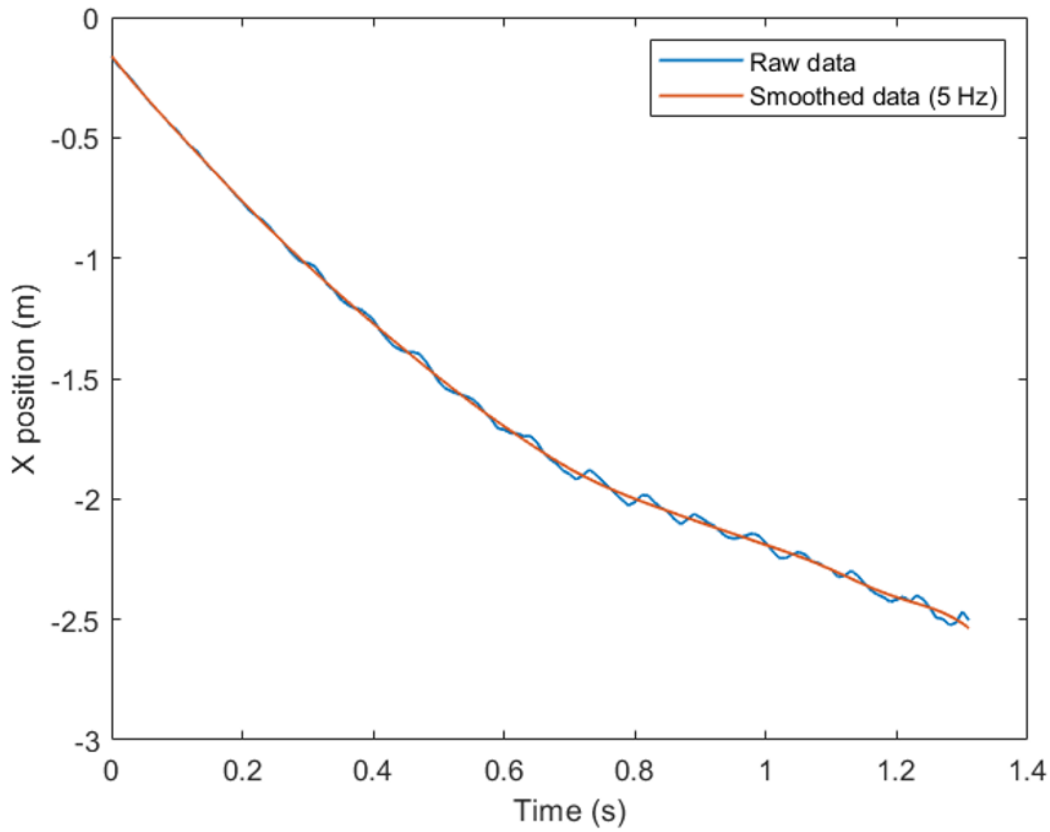


Figure 3. Butterworth Filter signal noise resolution. A 5Hz low-pass Butterworth filter was used to adjust minor irregularities in the flight path of the birds that result from potential data processing error and from the natural vertical oscillation inherent to flapping wings.

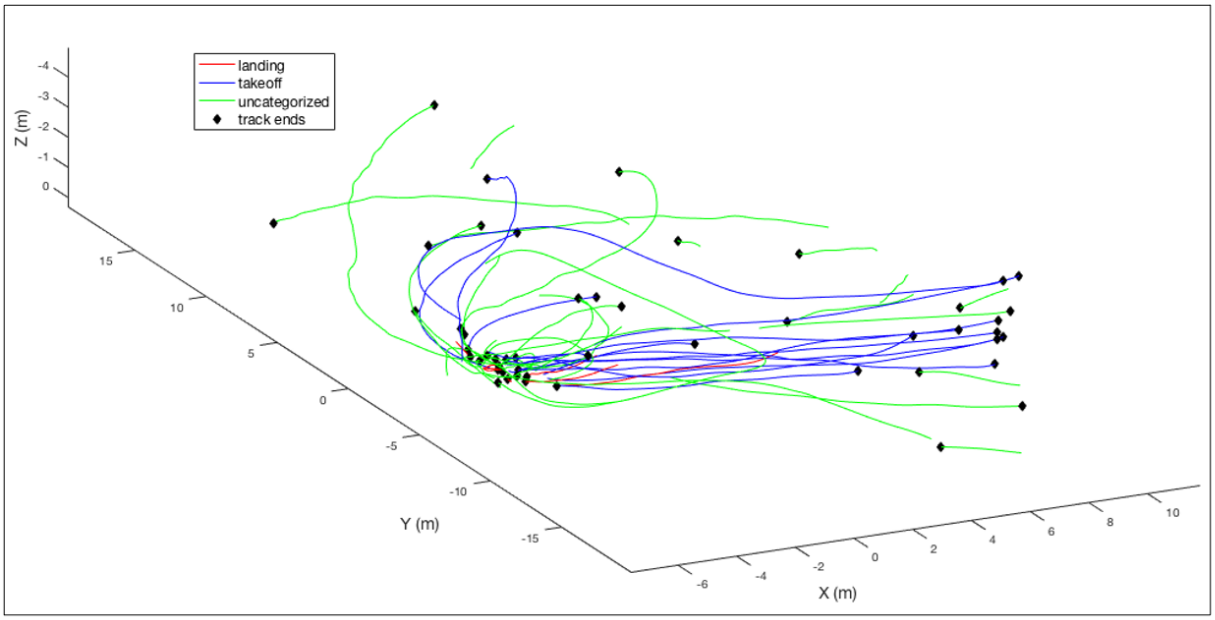


Figure 4. **Sample of 3D Trajectories.** Each bird track is depicted here in 3D space. The mud patch is where the flight paths converge near the origin of all three axes. Most bird tracks end either in the mud patch or in the bottom right corner of the graph, heading to the colony, but some go in other directions for unidentified reasons. The classifications of Landing, Takeoff and Uncategorized are a relic of earlier forms of analysis that bore no useful information but provide convenient visual contrast. Additionally, not all flight paths are shown for ease of reading the figure.

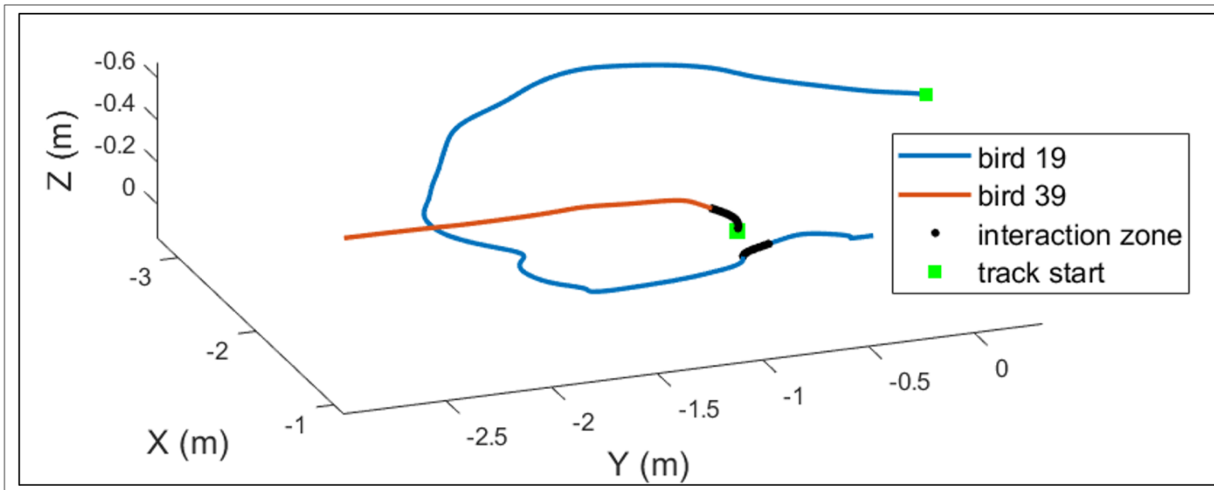


Figure 5. Interaction with high degree of collision avoidance. This interaction between birds 19 and 39 showed strong signs of collision avoidance on account of both change in speed (0.53 m/s) and change in angle (42.90 degrees). The angle change is particularly significant, being 1.48 standard deviations from the mean. Bird 39 only became visible at the start of the interaction and therefore has a shorter recorded flight path

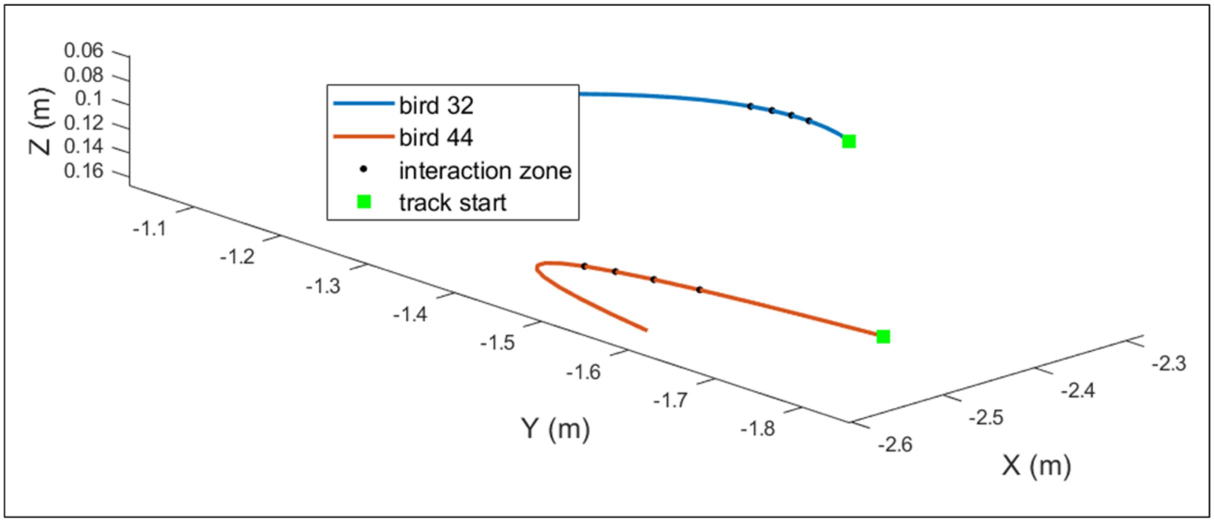
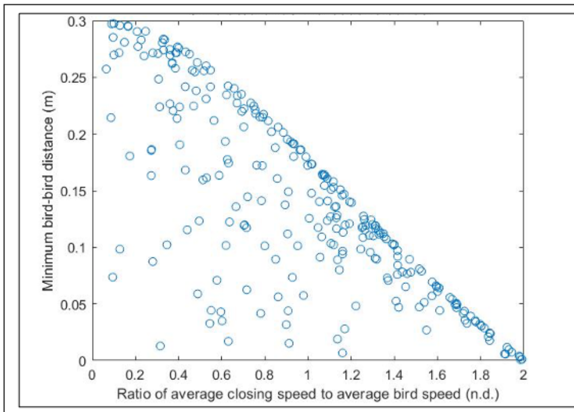


Figure 6. Interaction with low degree of collision avoidance. Birds 32 and 44 show few signs of collision avoidance, with a speed change of 0.12 m/s and an angle change of 0.91 degrees. Both of these values are well within 1 standard deviation of the mean for their respective sample means. although the birds may not appear to be on a collision course, they are quite close to each other and still change direction



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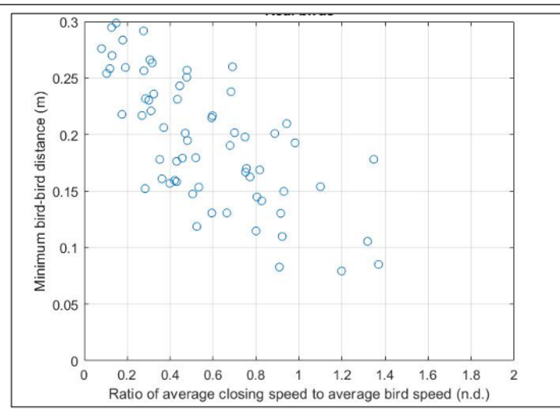

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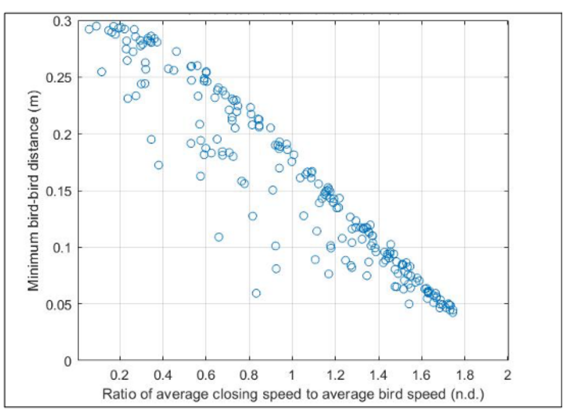

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Figure 7. Minimum Bird-Bird Distance Plotted Against the Ratio of Closing Speed to Average Speed. Chart A) A computer simulation of expected interaction data in the absence of collision avoidance behavior. B) A simulation of expected interaction data in the presence of collision avoidance behavior. C) Experimentally collected interaction data. The regression of the experimental data is $y = 0.2638 - 0.1226x$, the $r^2 = 0.49$, and $p = 0.0001$. This p value indicates statistical significance in this correlation.

Table 1. Differences in Closing and Departure Speeds and Angles of Select Interacting Birds.

Bird 1 ID	Bird 2 ID	Mean closing speed (m/s)	Mean departure speed (m/s)	Mean approach angle (degrees)	Mean departure angle (degrees)	ΔSpeed (abs v.)	ΔAngle (degrees)
1	49	-0.34	0.52	99.21	71.91	0.18	27.29
6	35	-4.07	4.37	127.02	136.29	0.30	9.27
19	39	-0.60	1.13	98.35	141.25	0.53	42.90
19	54	-1.03	1.34	125.09	134.2	0.32	9.11
25	29	-0.40	0.65	35.45	51.25	0.25	15.81
25	33	-1.02	0.37	114.53	125.43	0.65	10.90
32	44	-0.42	0.30	14.52	13.61	0.12	0.91
46	54	-1.32	1.22	43.37	53.91	0.10	10.54

Table 2. Summary of Close Interaction Statistics Across All Interactions

Variable	Mean	Maximum	Minimum	Median	SD
Overall Speed (m/s)	3.26	12.48	0.29	2.56	2.24
Closing Speed (m/s)	-1.49	-0.23	-7.41	-1.09	1.28
Departing Speed (m/s)	1.71	6.36	0.22	1.38	1.24
Change in Speed (m/s)	0.16	4.29	-6.12	0.01	1.37
Closing Angle (degrees)	63.1	163.32	4.06	52.01	42.09
Departing Angle (degrees)	61.0	163.24	4.36	45.90	43.22
Change in Angle (degrees)	0.30	70.89	-97.33	0.44	28.72
Interaction Elevation (m)	-0.03	0.32	-0.83	-0.03	0.22
Mean bird-bird distance (m)	0.24	0.30	0.15	0.24	0.03
Minimum bird-bird distance (m)	0.20	0.30	0.08	0.20	0.06

8 References

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